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Length-Based Risk Analysis (LBRA) for assessing sustainability of data-limited U.S. Caribbean reef fisheries

Jerald S. Ault[1], Laura Jay W. Grove[2], Jeremiah Blondeau[2], Kevin J. McCarthy[2]

[1]University of Miami, Rosenstiel School of Marine, Atmospheric and Earth Sciences, 4600 Rickenbacker Causeway, Miami, FL 33149

[2]National Marine Fisheries Service, Southeast Fisheries Science Center, 75 Virginia Beach Drive, Miami, FL 33149

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Summary

This study refined the data-limited, length-based stock assessment methodology and probabilistic risk analysis framework developed by Ault et al. (2019). The estimation–simulation approach used length-frequency data as the principal source of information in lieu of traditional catch and effort data. Four key developments distinguished the framework: (i) incorporation of probabilistic mortality and growth processes into a numerical cohort model; (ii) application of a precautionary approach for estimating sustainability reference points for fishing mortality F_{REF} and spawning biomass B_{REF}; (iii) characterization of sustainability in terms of probability distributions rather than deterministic point estimates; and (iv) evaluation of exploitation status using expected length-frequency distributions, the principal observable population metric available for many data-limited fisheries.

The refined length-based risk analysis (LBRA) framework was applied to three commercially and recreationally important coral reef fishes in the U.S. Caribbean ecosystem, including yellowtail snapper, queen triggerfish, and stoplight parrotfish. Population abundance-at-length data obtained from regional federal and territorial monitoring programs, together with updated life-history information, were integrated into a numerical cohort model to estimate sustainability metrics from a probabilistic perspective.

The LBRA framework provided a comprehensive evaluation of exploitation status at both the species and reef-fish community levels while offering a quantitative basis for evaluating alternative management strategies. By explicitly incorporating uncertainty in biological processes and fishery parameters, the approach estimates the likelihood that stocks are experiencing overfishing or have become overfished, thereby providing managers with a transparent measure of sustainability risk. The framework also facilitates evaluation of trade-offs among conservation objectives, fishery production, and socioeconomic outcomes under alternative harvest strategies.

The analyses indicate that reducing fishing mortality alone may not be sufficient to ensure long-term sustainability for all reef fish populations. Complementary management measures, including spatial and temporal protections that safeguard spawning aggregations and essential habitats, will likely be necessary to rebuild and maintain reproductive capacity. Although limited data often constrain conventional stock assessments, the LBRA framework establishes biologically based reference points and risk benchmarks that support science-based management in data-limited fisheries. In addition, the methodology provides an independent means of cross-validating results from more data-intensive assessment models where such analyses are

available. Overall, the framework offers a practical and precautionary approach for balancing sustainability risks with fishery production, reducing the probability of overfishing, and increasing the likelihood of sustaining coral reef fisheries over the long term.

1. Introduction

The ecological and economic importance of tropical multispecies coral reef fisheries makes their sustainable management a major conservation priority. Sustainability is defined as the ability of exploited fish stocks to continue producing goods and services while maintaining sufficient reproductive capacity to support this production indefinitely (Ault et al., 2014, 2019, 2022).

Commercial tropical reef fisheries are predominantly artisanal, consisting of numerous small vessels that land catches at many geographically dispersed ports (Gallucci et al., 1996). Recreational reef fisheries exhibit similar characteristics (Ault et al., 2005a). Consequently, estimating total landings and associated fishing effort is considerably more difficult than for industrial fisheries, which typically involve relatively few large vessels landing catches at a limited number of major ports. These characteristics often preclude the application of conventional stock assessment methods, including statistical catch-at-age, Stock Synthesis, and biomass dynamic models, because such approaches require long-term time series of reliable catch-at-age, fishing effort, and fleet-specific information that are generally unavailable for tropical reef fisheries (Ault and Olson, 1996; Quinn and Deriso, 1999; Walters and Martell, 2004; Haddon, 2011).

To overcome these limitations, Ault et al. (1998) developed a data-limited stock assessment methodology based on fish length-frequency data rather than catch and effort information. Their approach combined fishery-dependent and fishery-independent length-composition data with key life-history characteristics, including growth, longevity, and age at sexual maturity, within a numerical length-structured cohort model to estimate sustainability benchmarks such as spawning potential ratio (SPR). A central component of this framework was a length-based estimator of total mortality (Ehrhardt and Ault, 1992; Ault et al., 2005b, 2014).

More recently, fisheries stock assessments have increasingly adopted probabilistic approaches that explicitly account for uncertainty in fishery observations, biological parameters, and population dynamics. Rather than producing single deterministic estimates, these methods quantify uncertainty and evaluate management performance in terms of probabilities, such as the likelihood that a stock is being harvested sustainably (Francis, 1992; Hilborn and Walters, 1992; Methot and Wetzel, 2013; Punt et al., 2016; Link, 2018; Munyandorero, 2018). Such probabilistic assessments provide a more informative basis for risk-based fisheries management by explicitly characterizing the uncertainty associated with biological processes and management outcomes.

In this study, we refined the deterministic length-based framework of Ault et al. (1998, 2019) to a stochastic risk-analysis framework (Wagner, 1975; Keeney and Raiffa, 1976; Hertz and Thomas, 1983; Law and Kelton, 2000). Specifically, we: (i) incorporate probabilistic mortality and growth processes into the numerical cohort model; (ii) apply a precautionary approach for estimating biological reference points for fishing mortality (F_{REF}) and reproductive biomass (B_{REF}); (iii) quantify stock status and sustainability in terms of probability distributions rather than deterministic point estimates; and (iv) evaluate exploitation status using expected length-frequency distributions, the principal observable characteristic of exploited populations. We demonstrate the methodology using representative species from the exploited snapper–grouper complex of the U.S. Caribbean coral reef ecosystem and show how the resulting probabilistic framework can be used to evaluate sustainability status and compare alternative fishery management strategies under uncertainty.

2.0 Method Description

2.0.0 Demographic parameters and estimation of mortality rates

The "data-limited" assessment approach developed by Ault et al. (1998, 2022, 2024) requires a small number of species-specific life history demographic parameters: (i) the von Bertalanffy growth function relating length to age [Table 1, Equation (T-1)]; (ii) the allometric weight–length relationship [Table 1, Equation (T-2)]; (iii) maximum observed age (a_λ); and, (iv) the length at which 50% of individuals attain sexual maturity (L_m) (c.f. Table 1). The principal fishery data required are abundance-at-length compositions, from which the indicator variable $\bar{L}$, defined as the mean length of fish in the exploited phase of the population (i.e., individuals larger than the minimum length of first capture, L_c, regulated by the fishery). This information is subsequently used to estimate instantaneous total (Z), natural (M), and fishing (F) mortality rates.

Instantaneous total mortality Z was estimated using the theoretical definition of mean exploited length developed by Ault and Ehrhardt (1991) and Ehrhardt and Ault (1992) for the truncated age-structured population model,

$$\bar{L}(t) = \frac{F(t)\int_{a_c}^{a_\lambda} N(a,t)L(a,t)da}{F(t)\int_{a_c}^{a_\lambda} N(a,t)da} \tag{1}$$

where $N(a,t)$ is abundance at age (a) and time (t), $L(a,t)$ is length at age, $F(t)$ is the instantaneous fishing mortality rate, and a_c is the age at first capture. For exploited populations, $\bar{L}(t)$ in Equation (1) reflects changes in population size structure caused by total mortality and therefore provides an estimator of $Z(a,t)$ (Beverton and Holt,1957; Ehrhardt and Ault, 1992; Quinn and Deriso, 1999).

Substituting the von Bertalanffy model for $L(a,t)$ and the exponential survivorship model for $N(a,t)$ [Table 1, Equation (T-3)] into Equation (1), and simplifying algebraically, yields the estimator for total mortality (a,t) derived by Ehrhardt and Ault (1992),

$$\left[\frac{L_\infty - L_\lambda}{L_\infty - L_c}\right]^{\frac{\hat{Z}(t)}{K}} = \frac{\hat{Z}(t)\left(L_c - \bar{L}(t)\right) + K\left(L_\infty - \bar{L}(t)\right)}{\hat{Z}(t)\left(L_\lambda - \bar{L}(t)\right) + K\left(L_\infty - \bar{L}(t)\right)} \tag{2}$$

where K and L_∞ are von Bertalanffy growth parameters, L_c is minimum length at first capture, and L_λ is expected length at maximum age a_λ [Table 1, Equation (T-4)]. Estimates of Z were obtained numerically using the LBAR algorithm (Ault et al., 1996; FAO, 2003). Unlike classical length-based mortality estimators that assume an infinite lifespan (Beverton and Holt, 1957), Equations (1) and (2) explicitly assume a finite maximum age (a_λ), thereby reducing potential bias in mortality estimates for relatively short-lived species (Ehrhardt and Ault, 1992).

Natural mortality rate M was estimated from maximum observed lifespan following the survivorship formulation of Alagaraja (1984), Hewitt and Hoenig (2005) and Hamel and Cope, 2022),

$$S(a_\lambda) = \frac{N(a_\lambda)}{N(a_c)} = e^{-M(a_\lambda - a_c)} \quad (3)$$

where $S(a_\lambda)$ denotes survivorship from recruitment age a_r to the maximum observed age a_λ. Assuming recruitment occurs at birth, $a_r = 0$, Equation (3) yields the estimator for natural mortality rate,

$$\widehat{M} = \frac{-\ln[S(\hat{a}_\lambda)]}{\hat{a}_\lambda} \quad (4)$$

where $\tilde{a}_\lambda$ is the observed maximum age. Following a heuristic proposed by Hewitt and Hoenig (2005), survivorship at maximum observed age was assumed to be 5%, i.e. $S(\tilde{a}_\lambda) = 0.05$. This contrasts with survivorship values of 1% or 0.45% commonly assumed for unexploited populations (Quinn and Deriso, 1999; Cope and Hamel, 2022)]. Fishing mortality was estimated as $\hat{F} = \hat{Z} - \widehat{M}$.

For application to reef fishes in the U.S. Caribbean, species-specific life-history parameters for snapper and grouper species were obtained from the synthesis of Stevens et al. (2019). Population length-composition data were obtained from the NOAA Southeast Fisheries Science Center through two regional monitoring programs: (i) the National Coral Reef Monitoring Program (NCRMP) Reef Fish Visual Census (RVC), a fishery-independent underwater visual survey (Blondeau et al., 2026); and (ii) the Trip Interview Program (TIP), a dockside intercept survey of the commercial fishery (K. McCarthy, pers. comm.).

Mean exploited length $\bar{L}(t)$ was estimated using the design ratio-of-means estimator (Cochran, 1977; Lohr, 2010),

$$\bar{L}(t) = \frac{\bar{y}}{\bar{x}} = \frac{\frac{\sum y_i}{n}}{\frac{\sum x_i}{n}}$$

which follows directly from the formal definition of mean length in the exploited phase of the population [Equation (1); Beverton and Holt, 1957]. Here x_i denotes the number of fish measured in sampling unit i (e.g., RVC survey, fishing trip, etc.), y_i is the corresponding sum of measured fish lengths in unit i, and *n* is the total number of sampling units. Variance estimates for of $\bar{L}(t)$ were computed following the procedures described by Lohr (2010).

2.0.1 Numerical length-based cohort model

The numerical length-based cohort model REEFS (Reef-fish Exploited Ecosystem Fishery Simulator) developed by Ault et al. (1998) for data-limited fisheries and was extended to incorporate stochastic mortality and growth processes. The original model was based on the population conservation equation,

$$\frac{dN(a,t)}{dt} = \frac{\partial N(a,t)}{\partial a} + \frac{\partial N(a,t)}{\partial t} = -Z(a,t)N(a,t) \qquad (5)$$

where $N(a,t)$ is the abundance of fish at age (a) and time (t), and $Z(a,t)$ is the instantaneous total mortality rate. The partial differential equation describes changes in population age structure through time as a consequence or mortality and ageing.

The REEFS model incorporates the principal demographic processes characteristic of tropical marine fishes, including continuous somatic growth, protracted spawning and recruitment seasons, and density-dependent population dynamics (Ault and Fox, 1989; Sparre and Venema, 1992; Ault and Olson, 1996; Ault et al., 1999). Individual cohorts are tracked through time in terms of numbers-at-age, length, and body weight using the demographic relationships summarized in Table 1.

For the present study, the deterministic model of Ault et al. (1998) was modified by incorporating stochastic variation in mortality and growth parameters, thereby allowing uncertainty in demographic processes to propagate through all model-derived sustainability metrics. Model simulations were conducted using a monthly time step ($\Delta t = 1/12$ year), with annual recruitment distributed equally among the twelve monthly intervals.

Consistent with the data-limited formulation of the model, the following simplifying assumptions were adopted: (i) mean annual recruitment was constant through time; (ii) recruitment was apportioned uniformly among monthly time steps; (iii) sexual maturity occurred at a knife-edged length threshold L_m; and (iv) fishery selectivity followed a knife-edged pattern at the minimum length of first capture L_c.

2.0.2 Probabilistic mortality rates

Uncertainty in total mortality (Z) was quantified from the sampling properties of the survey estimate of mean exploited length, $\bar{L}$. Under the design-based sampling framework, estimates of $\bar{L}$ are approximately normally distributed (Lohr, 2010). Accordingly, a normal probability density function, $N(\mu, \sigma^2)$, was parameterized with mean $(\mu = \bar{L})$ and variance $\left(\sigma^2 = \left[\mathrm{SE}\left(\bar{L}(t)\right)\right]^2\right)$. Random realizations of $\bar{L}$ were generated from this distribution and converted to corresponding estimates of total mortality by solving Equation (2).

Uncertainty in natural mortality (M) was derived from uncertainty in maximum age a_λ using Equation (4). As demographic information for U.S. Caribbean reef fishes has improved over the past two decades, reported maximum ages have frequently increased, in some cases doubling or tripling previous estimates (e.g., Claro, 1981; Mason and Manooch, 1985; O'Hop et al., 2015; Stevens et al., 2019; Shervette et al., 2025). Consequently, the observed maximum age, $\hat{a}_\lambda$, was regarded as a lower bound, with uncertainty extending only toward older ages. An exponential probability density function, expo(β) (Law and Kelton, 2000), was therefore selected because it is bounded below at zero and possesses a long positive tail consistent with this asymmetric uncertainty.

The exponential distribution was parameterized in several steps. First, the estimate of natural mortality obtained from Equation (4) and the observed maximum age ((\hat a_\lambda)) were used to estimate a theoretical maximum age $\tilde{a}_\lambda$ by rearranging Equation (4),

$$\tilde{a}_\lambda = \frac{-\ln[S(\tilde{a}_\lambda)]}{\hat{M}} \tag{6}$$

assuming survivorship to the theoretical maximum age was 0.45%, i.e., $S(\tilde{a}_\lambda) = 0.0045$). The interval between the observed and theoretical maximum ages was then calculated as

$$\Delta a_\lambda = \tilde{a}_\lambda - \hat{a}_\lambda \tag{7}$$

Random realizations from the exponential distribution represent ages beyond the observed maximum age, such that zero corresponds to $\hat{a}_\lambda$. The exponential rate parameter $1/\beta$ was estimated as

$$\frac{1}{\beta} = \frac{-\ln(0.0045)}{\Delta a_\lambda} \tag{8}$$

which defines an expo(β) distribution with approximately 99.9% of realizations occurring within the interval Δa_λ. Each simulated realization was converted to an actual maximum age by adding $\hat{a}_\lambda$, after which Equation (4) was used to compute the corresponding realization of natural mortality.

For each Monte Carlo iteration, a random draw of total mortality (Z) was paired with a corresponding realization of natural mortality (M), and fishing mortality was calculated as

$$F = Z - M$$

These mortality estimates served as inputs to a single simulation of the REEFS numerical cohort model. For each species, $n = 10{,}000$ Monte Carlo simulations were performed to ensure stable estimates of the resulting probability distributions and associated sustainability metrics.

2.0.3 Probabilistic length-at-age

Variation in length-at-age about the von Bertalanffy growth curve was assumed to follow a normal distribution with a constant coefficient of variation (CV = standard deviation/mean) of 7%, consistent with growth variability reported for a broad range of marine fish species (e.g., Then et al., 2015). For each age (a), length was therefore represented as $\mu = \bar{L}(a)$ and $\sigma^2 = [0.07\bar{L}(a)]$, where $\bar{L}(a,t)$ is the expected length predicted by the von Bertalanffy growth model.

This variability was incorporated directly into the numerical cohort model. At each model age, a normal distribution was parameterized using the predicted mean length and the corresponding standard deviation $\left(\sigma = \sqrt{[0.07\bar{L}(a)]}\right)$. Individual lengths for the $N(a,t)$ fish comprising each cohort were then generated by random sampling from this distribution, truncated at 3σ to exclude biologically unrealistic values.

The resulting length distribution at each age was represented by a histogram consisting of 31 equal-width length classes spanning the truncated distribution (15 classes above and 15 classes below the mean, together with the central class). These length sub-cohorts were then tracked through the numerical simulation and used to compute size-dependent quantities, including biomass, reproductive output, fishery yield, and length-frequency distributions.

2.0.4 Sustainability analyses

The numerical cohort model was used to evaluate the sustainability of exploited reef fish populations by comparing population metrics at current fishing mortality, (F(t)), with precautionary management reference points. Three principal metrics were calculated: exploitable biomass (B_{EX}), yield in weight (Y_{w}), and spawning stock biomass (SSB). Biomass at age and time was estimated as the product of abundance $N(a,t)$ and individual weight $W(a,t)$. Exploitable biomass was calculated by integrating biomass over the exploited length range at a particular time t,

$$B_{EX}(L_c,t) = \int_{L_c}^{L_\lambda} B(L|a)\phi(L)dL = \int_{L_c}^{L_\lambda} N(L|a)W(L|a)\phi(L)dL \qquad (9)$$

where $L|a,t$ denotes the distribution of lengths at age (a) and time (t), $\phi(L)$ is gear selectivity at length, and L_λ is the distribution of lengths at the maximum age a_λ. Yield in weight was then calculated as

$$Y_{\mathrm{w}}(F.L_c,t) = F(t)B_{EX}(L_c,t). \qquad (10)$$

Spawning stock biomass was estimated by integrating biomass over the mature component of the population,

$$\mathrm{SSB}(t) = \int_{L_m}^{L_\lambda} B(L|a,t)dL \qquad (11)$$

where L_m is the length at 50% maturity. In Equations (9)–(11), all individuals larger than L_c or L_m were included in the integrations.

Spawning potential ratio (SPR), a widely used measure of reproductive capacity (Ault et al., 2014, 2022), was calculated as the ratio of spawning biomass under the current fishing mortality to that of an unfished population,

$$\mathrm{SPR} = \frac{\mathrm{SSB}_{F(t)}}{\mathrm{SSB}_{F=0}} \qquad (12)$$

To establish precautionary sustainability reference points, we adopted the demographic framework of Ault et al. (2019), based on three principles: (i) setting $L_c = L_m$, thereby allowing fish at least one spawning opportunity before recruitment to the fishery (Beverton and Holt, 1957; Ricker, 1975); (ii) assuming $F = M$ as a proxy for F_{MSY} (Mace, 2001); and (iii) treating MSY as a management limit rather than a target (Caddy and McGarvey, 1996; Caddy, 2004). The numerical cohort model was applied to representative grouper (Epinephelidae), snapper (Lutjanidae), triggerfish, and parrotfish species from the U.S. Caribbean to estimate SPR at F_{MSY}. For each family, the mean SPR at MSY was rounded to the nearest 5% increment and adopted as the family-specific reference SPR. The fishing mortality reference point, F_{REF}, was defined as the fishing mortality producing this reference SPR.

The biomass reference point, B_{REF}, was defined as the spawning biomass at F_{REF},

$$\frac{B}{B_{\text{REF}}} = \frac{\text{SSB}_{F(t)}}{\text{SSB}_{F_{\text{REF}}}} \tag{13}$$

The simulated distributions of fishing mortality and the associated reference points were used to estimate probability distributions for the principal sustainability benchmarks: SPR, F/F_{REF} (commonly termed the overfishing limit, OFL), and B/B_{REF}. Sustainability risk was quantified as the probability that SPR fell below the reference SPR, that F/F_{REF} exceeded 1.0, or that B/B_{REF} was less than 1.0. These probabilities represent the risks of impaired reproductive capacity, excessive fishing mortality (fleet overcapitalization) and suboptimal yields, and insufficient spawning biomass to sustain the population, respectively.

Finally, the numerical cohort model was used to compute response surfaces ("isopleths") of yield (Y_{w}) and SPR over the full range of biologically feasible combinations of fishing mortality ((F)) and length at first capture (L_c) (Beverton and Holt, 1957). These isopleth analyses provide a framework for evaluating current exploitation relative to sustainability reference points and for exploring alternative harvest strategies that balance fishery production with conservation objectives.

The resulting stochastic length-based risk analysis framework combines demographic uncertainty, probabilistic mortality estimation, and numerical cohort simulation to estimate distributions of sustainability metrics and associated management reference points. The framework provides a practical approach for evaluating exploitation risk in data-limited coral reef fisheries using routinely collected length-frequency data.

2.1.0 Data Inputs

2.1.1 Model parameters

The sustainability risk analysis methodology was applied to three principal exploited reef fish species in the US Caribbean region, consisting of: yellowtail snapper (Ocyurus chrysurus); Queen triggerfish; and Stoplight parrotfish.

The life history demographic parameters for these example species are provided in Table 2. Average length in the exploited phase was estimated from length composition data for the recent period 2016–2025 for each of the statistical sampling programs (Table 3). Annual survey estimates of mean and variance of L were weighted by annual sample size to produce the time period values. Although the four sampling programs collected information from reef habitats in the US Caribbean, no single survey encompassed the full range of habitats for the three species: the fishery independent diving survey was restricted to depths <33 m, and TIP commercial fishing was spatially restricted. To obtain representative population values, composite L and SE(L) were estimated for each species by taking the respective arithmetic means of $\bar{L}$ and var($\bar{L}$) from the data sources and island regions. The composite $\bar{L}$ was then used to compute total mortality rate $\hat{Z}$ (Table 3) and subsequent estimates of fishing mortality rate $\hat{F}$ (Table 4).

- **Representative length-structured abundance & biomass**.
- **Mean exploited length**: $\bar{L}$ (theoretically equivalent for fishery-dependent and fishery-independent surveys).

Life history parameters:
- Minimum length at first capture (L_c)
- Maximum observed age under exploitation ($a_{\max}$)
- Theoretical maximum age $\left(a_\lambda \rightarrow M(n)\right)$
- Mean length at theoretical maximum age (L_λ)
- Length at 50% maturity (L_m)
- Von Bertalanffy growth parameters: (L_∞, K, a_0)
- Probability of observing length L at age a: $f(L|a)$
- Length-weight relationship: $W = \alpha L^\beta$
- Mean weight at theoretical maximum age (W_λ)

Fishery data
- Landings (recruitment scaling)
- fishing effort

2.2 Analyses & Data Outputs
- **LBAR simulations**: $\bar{L}(n) \rightarrow Z(n) \rightarrow F(n)$: (typically $n =$ 10,000 Monte Carlo simulations).
- **REEFS (Reef Ecosystem Exploited Fishery Simulation)**:
  - $F(n) \rightarrow$ Likelihoods distributions
  - Limit Control Rule components
  - Spawning Potential Ratio (SPR): $SPR \rightarrow B/B_{\mathrm{REF}}$
  - Overfishing Limit (OFL): $OFL \rightarrow F/F_{\mathrm{REF}}$
- **Risk Probabilities** for recruitment and growth overfishing.
- **Management forecasts** under alternative harvest scenarios

2.3 Implications for Management

How can LBRA inform fisheries management?
- Rapidly **identify** species at greatest risk of recruitment and growth overfishing.
- **Prioritize** species and stocks for assessment, monitoring, and management action.
- **Define** the management decision space by quantifying the probabilities of recruitment and growth overfishing.

- **Evaluate** management scenarios by forecasting the likelihood and time horizon for achieving biological and harvest objectives.
- **Cross-validate** integrated stock assessments (e.g., Stock Synthesis) using an independent analytical framework based on the same underlying population dynamics.
- **Facilitate** multi-species and ecosystem comparisons **using** a consistent analytical framework.
- **Support precautionary management** in data-limited fisheries by providing biologically informed reference points and risk estimates.
- **Improve** management transparency by explicitly linking management actions to quantified biological risk.

2.4 Caveats

- **Requires** representative sampling; reliable life-history parameters; and relatively stable recruitment.
- **Estimates** total mortality $(\hat{Z})$; it does **not** partition fishing mortality among fleets $(f_1 \cdots f_{\mathrm{n}})$.
- **Assuming** the observed length distribution is not substantially biased by gear selectivity or habitat-specific sampling.

A constraint of the LBRA method is that it does not allow for the separation of commercial and recreational fleet effects in total mortality estimation. However, for data limited situations the LBRA does provide valuable insights into the stock status that can provide guidance for management decisions. For example, identification of the minimum sustainable population size (i.e., > 40% SPR), accepting the necessary trade-offs between what is taken out and what is left in the water. The simulation methods of our numerical model allowed insights into the transitional (non-equilibrium) stock dynamics. These showed that stock recovery times varied relative to the species' life history demographics, and that substantial lead time must be built into expectations for stock recovery. In summary, the LBRA data-limited method provides a consistent basis for cross-checking outputs of contemporaneous high-parameter age-based statistical stock assessment models.

3.0 Applications of the Method

See Figures & Tables.

4.0 Discussion

4.1. Business-as-Usual (BAU) strategy

The business-as-usual (BAU) management strategy was evaluated to characterize current exploitation patterns and to provide a baseline against which alternative management strategies could be compared. Kobe strategy plots based on the decision metrics F/F_{REF} and B/B_{REF} indicated that the three representative reef fish species were subject to high exploitation pressure, with a high probability of overfishing and depleted spawning biomass relative to sustainability reference points.

Despite the ecological and economic importance of coral reef fisheries, relatively few US Caribbean reef fish stocks have undergone comprehensive stock assessments through NOAA's Southeast Data, Assessment, and Review (SEDAR) program. Consequently, many management decisions continue to rely on limited biological information while fishing pressure remains high. The LBRA results demonstrate that current BAU regulations are unlikely to achieve long-term sustainability objectives, as reflected by the high probabilities of exceeding fishing mortality limits and falling below spawning biomass reference points. These findings are also consistent with evidence of excessive fishing capacity, particularly within the recreational sector, where fishing power deployed per unit area and time substantially exceeds sustainable levels.

The analyses indicate that maintaining current regulations will not achieve sustainable exploitation of these reef fish populations. Management strategies that reduce fishing mortality, increase size at first capture, or combine both measures are therefore required to rebuild spawning biomass, reduce the probability of overfishing, and sustain long-term fishery production. As fishing demand continues to increase throughout the U.S. Caribbean and southern Florida, precautionary management strategies that explicitly balance production objectives with sustainability risk will become increasingly important.

4.2. Limit Strategy

To evaluate management options for reducing systemic overfishing, we compared three management strategies: (1) Business-as-Usual (BAU); (2) Limit; and (3) Target. The Limit Strategy (LS) adopted the precautionary fishing mortality reference point $F_{40\%\mathrm{SPR}}$, equivalent to the limit reference fishing mortality F_{REF} proposed by Ault et al. (2019). Under the LS, fishing mortality was maintained at the BAU level while the minimum length at first capture (L_c) was increased until the deterministic spawning potential ratio reached at least 40%. This represented the minimum management intervention required to reduce overfishing risk while preserving fishery production. However, the probabilistic analyses showed that increasing (L_c) alone was generally insufficient to achieve sustainability. Although SPR increased substantially, the probability of meeting sustainability objectives improved only to approximately 50% for the species evaluated. These results indicate that protecting juvenile fish by increasing size at first capture can partially rebuild reproductive capacity but cannot fully compensate for excessive fishing mortality.

This outcome is consistent with management actions implemented in southern Florida, where increases in minimum size limits have often occurred without corresponding reductions in fishing effort. While increasing L_c shifts harvest toward larger, more productive individuals and improves spawning biomass, fishing mortality remains sufficiently high that sustainability risks persist. Yield in weight (Y_{w}) changes relatively little over a wide range of fishing mortality rates, whereas SPR continues to increase with larger L_c, illustrating that size regulations alone provide diminishing returns as fishing pressure intensifies.

Conceptually, if recruitment remains stable, increasing L_c could maintain SPR near 40% even under very high fishing mortality because individuals would be allowed to reproduce before entering the fishery. In practice, however, such conditions are unrealistic. High fishing mortality reduces the abundance of larger spawning adults, increases variability in recruitment, and elevates the risk of stock depletion. Consequently, achieving long-term sustainability requires management measures that directly reduce fishing mortality in addition to increasing size at first capture. As demand for reef fish continues to grow, effective management will require controls on both fishing mortality and harvest selectivity to balance fishery production with sustainability risk.

4.3. Target strategy

Substantial reductions in sustainability risk for overexploited reef fish populations in southern Florida were achieved under the **Target Strategy (TS)**. This strategy combined the increased minimum length at first capture (L_c) established under the **Limit Strategy** (i.e., the length required to achieve a deterministic SPR of 40%) with a 50% reduction in fishing mortality relative to business-as-usual (BAU) conditions.

Whereas the Limit Strategy reduced sustainability risks to approximately 50%, leaving stocks close to the threshold between sustainable and unsustainable exploitation, the Target Strategy reduced the estimated risks to near zero. This buffer was intentionally incorporated because the present analyses did not explicitly account for additional sources of mortality, such as catch-and-release mortality, nor other uncertainties that could further reduce stock productivity. Consequently, the Target Strategy provides a precautionary margin of safety above the minimum sustainability threshold.

Although the proposed Target Strategy may appear conservative, it should be viewed as an initial management benchmark rather than a fixed prescription. The acceptable level of sustainability risk is ultimately a policy decision that should be determined jointly by fishery managers, stakeholders, and scientists and may differ among species according to their ecological, economic, and social importance.

The analyses indicate that meaningful reductions in sustainability risk cannot be achieved through increases in minimum size limits alone. Instead, effective rebuilding of overexploited reef fish populations requires a combination of larger minimum size limits and substantial reductions in fishing mortality. Such reductions could be achieved through a variety of complementary management measures, including limited-entry programs, harvest quotas, bag limits, seasonal closures, effort controls, and no-take marine reserves. Evaluating the relative biological effectiveness and socioeconomic consequences of these alternative management options represents an important area for future research and adaptive fisheries management.

4.4. Reflections on the analytical approach and its challenges

The length-based risk analysis (LBRA) framework provides a practical approach for evaluating sustainability in data-limited fisheries by integrating biological observations, demographic relationships, and stochastic simulation within a harvest control rule (HCR) framework. Using probability distributions rather than deterministic point estimates, the approach allows direct evaluation of (i) current stock status and (ii) current fishing mortality relative to biological reference points (Methot et al., 2014; Maunder et al., 2020). Although HCRs are a fundamental component of U.S. Fishery Management Plans, their effectiveness ultimately depends on the quality of available demographic information and the ability to characterize uncertainty in population processes (Maunder and Piner, 2014). The LBRA framework provides a transparent means of integrating these uncertainties when conventional stock assessment methods are not feasible.

Our analyses demonstrated that the current business-as-usual (BAU) management strategy carries a high probability of unsustainable exploitation, while the Limit Strategy reduced, but did not eliminate, sustainability risk. In contrast, the Target Strategy, which combined increased minimum size limits with substantial reductions in fishing mortality, produced a marked reduction in the probability of overfishing and rebuilding failure. These findings indicate that regulations based solely on minimum size limits are unlikely to achieve sustainable exploitation and that effective management requires coordinated controls on both harvest selectivity and fishing mortality.

Implementing such strategies throughout the U.S. Caribbean reef fish community presents both biological and socioeconomic challenges. Successful rehabilitation of reef fish populations will require coordinated management actions by regulatory agencies together with broad stakeholder participation. In addition to size limits and fishing mortality controls, complementary management measures—including limited-entry programs, bag limits, seasonal closures, effort controls, and no-take marine reserves—should be evaluated within an adaptive management framework. Because reef fish species differ substantially in their life-history characteristics and exploitation patterns, management measures should be evaluated at both species and community levels.

The LBRA framework provides managers with a quantitative basis for comparing alternative harvest control rules and explicitly evaluating the trade-offs between fishery production and sustainability risk. As additional biological and fishery data become available, the approach can be refined to improve estimates of demographic parameters, reference points, and recovery trajectories. Given the extended rebuilding times projected under current conditions, prompt implementation of management strategies that simultaneously address minimum size limits, fishing mortality, spatial protection, and seasonal closures will be essential to restore exploited reef fish populations and sustain the ecological and economic services they provide.

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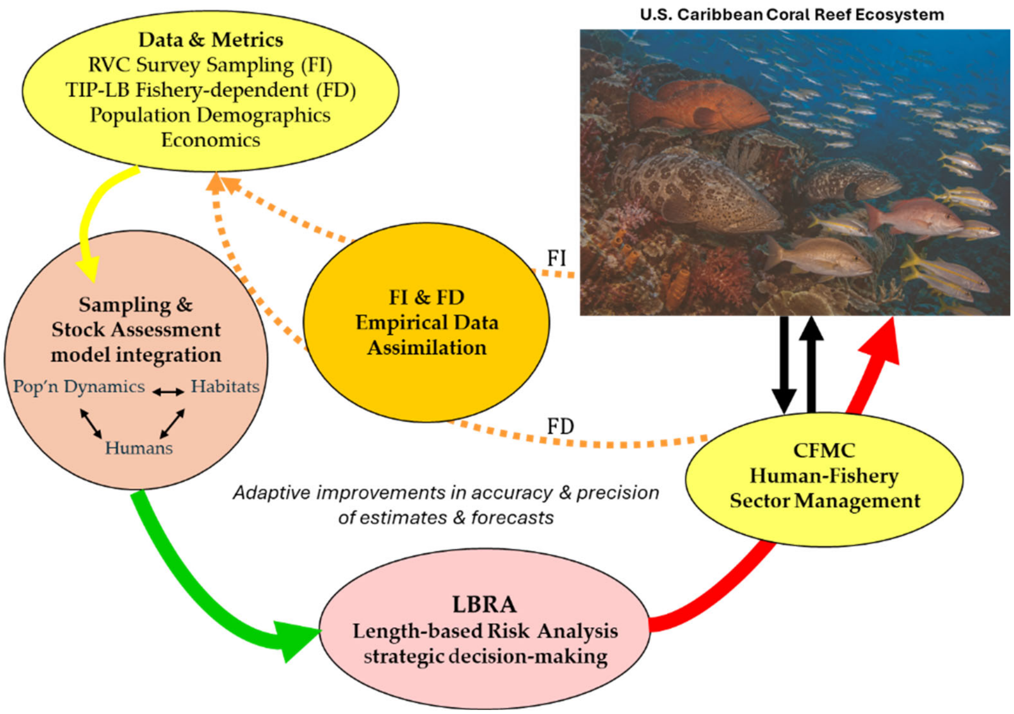


Figure 1.- Systems analysis framework underlying the Length-based Risk Analysis (LBRA) methodology developed by Ault et al. (2005, 2019, 2022, 2024). The framework illustrates the adaptive integration of fishery-independent (FI) and fishery-dependent (FD) data to improve the accuracy and precision of stock assessment estimates, sustainability metrics, and management forecasts.

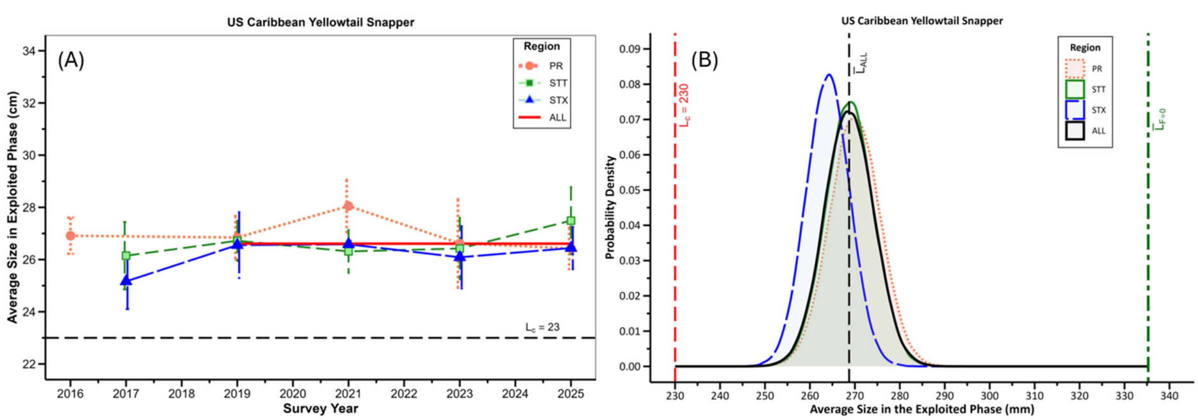


Figure 2.- Mean length in the exploitable phase of the population $(\bar{L})$ and associated 95% confidence intervals for U.S. Caribbean yellowtail snapper in Puerto Rico (PR), St. Thomas (STT), St. Croix (STX), and all island regions combined (ALL). (A) Annual estimates for 2016–2025. (B) Corresponding probability density distributions of $\bar{L}$. The horizontal dashed green line in panel (A) and the vertical dashed red line in panel (B) indicate the minimum length at first capture (L_c). The vertical dashed green line in panel (B) denotes the expected mean length of an unexploited population.

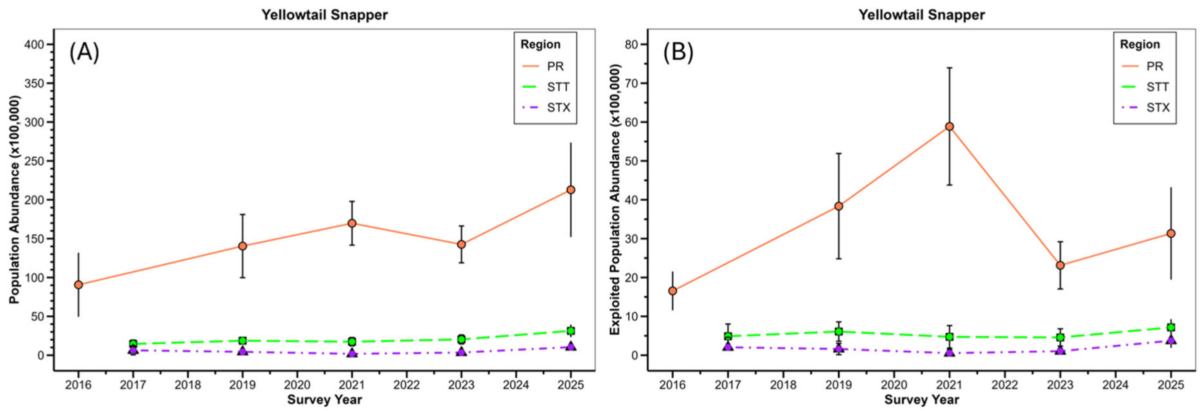


Figure 3.- Estimated absolute abundance (mean ± 95% confidence interval) of U.S. Caribbean yellowtail snapper from Reef Visual Census (RVC) surveys conducted during 2016–2025 in Puerto Rico (PR), St. Thomas (STT), and St. Croix (STX). Estimates are shown for two population phases: (A) the entire population ($L_r \rightarrow L_\lambda$); and (B) the exploitable population ($L_c \rightarrow L_\lambda$), comprising individuals >230 mm fork length (FL).

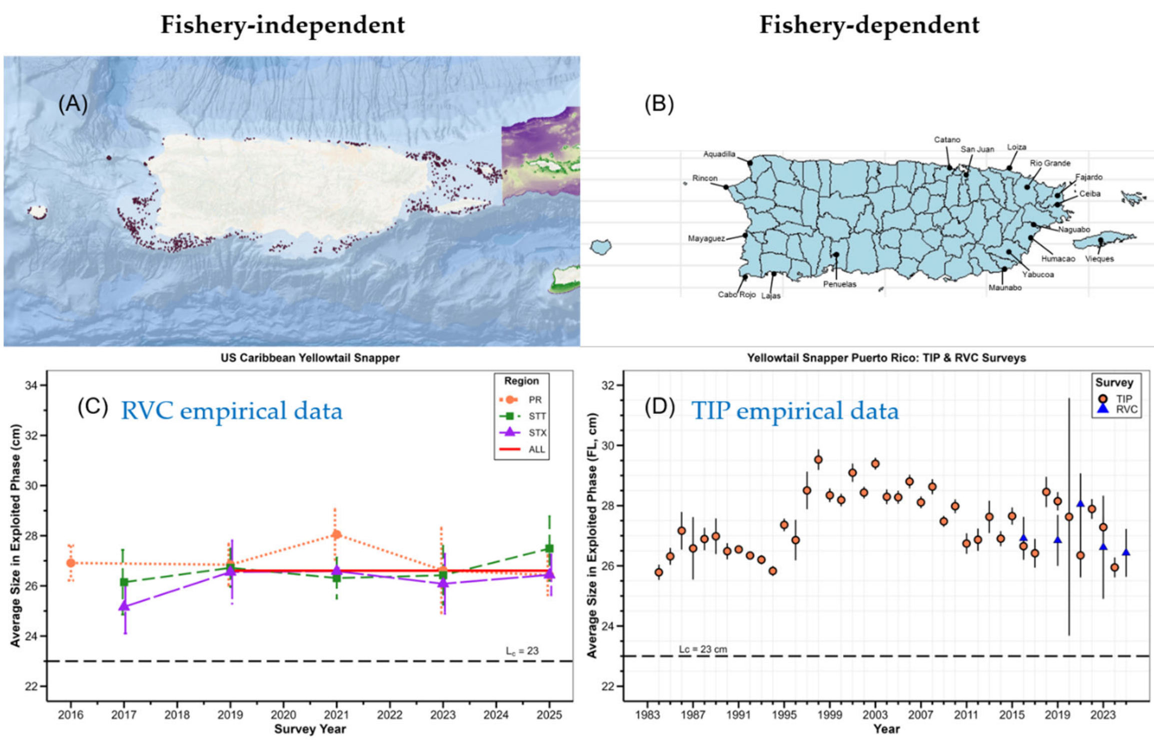


Figure 4.- Fishery-independent National Coral Reef Monitoring Program (NCRMP) Reef Visual Census (RVC) and fishery-dependent Trip Interview Program (TIP) sampling for U.S. Caribbean yellowtail snapper. (A) Locations of RVC sampling sites in Puerto Rico, 2016–2025. (B) Locations of TIP sampling sites in Puerto Rico, 1983–2025. (C) Annual RVC estimates of mean length in the exploitable phase of the population ($\bar{L}$) and associated 95% confidence intervals for Puerto Rico (PR), St. Thomas (STT), St. Croix (STX), and all island regions combined (ALL). (D) Comparison of RVC and TIP estimates of mean exploitable length ($\bar{L}$) for Puerto Rico, 1983–2025.

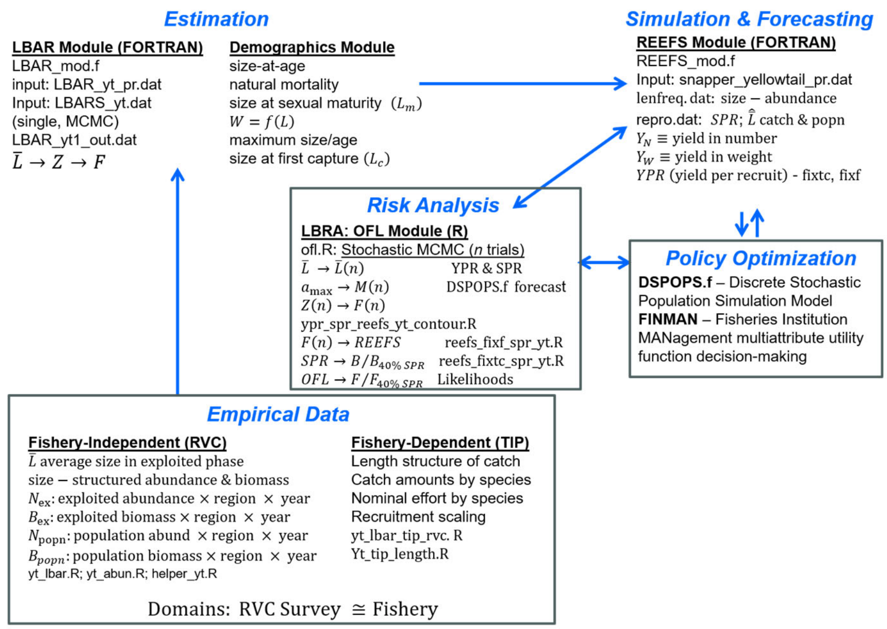


Figure 5.- Data, analytical, and modeling workflow for the Length-based Risk Analysis (LBRA) framework developed by Ault et al. (2005, 2019, 2022, 2024). The diagram illustrates the progression from fishery-independent and fishery-dependent data collection through analytical estimation, numerical population modeling, stochastic risk analysis, and derivation of sustainability reference points and management performance metrics.

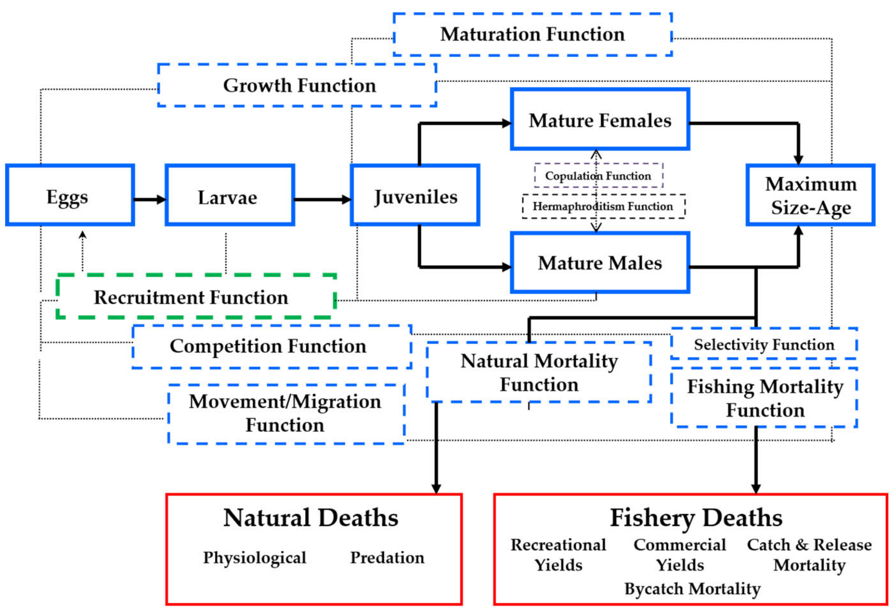
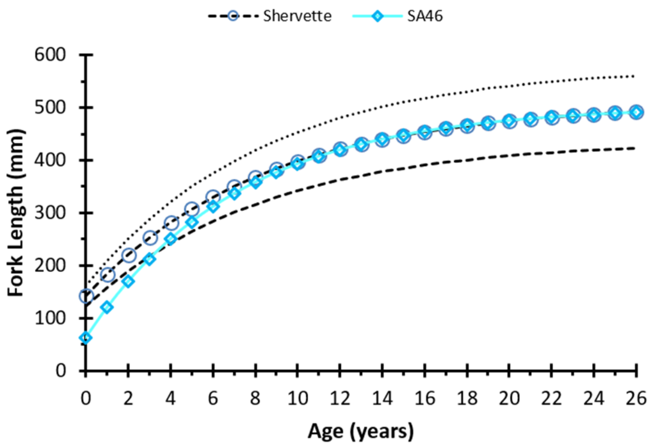
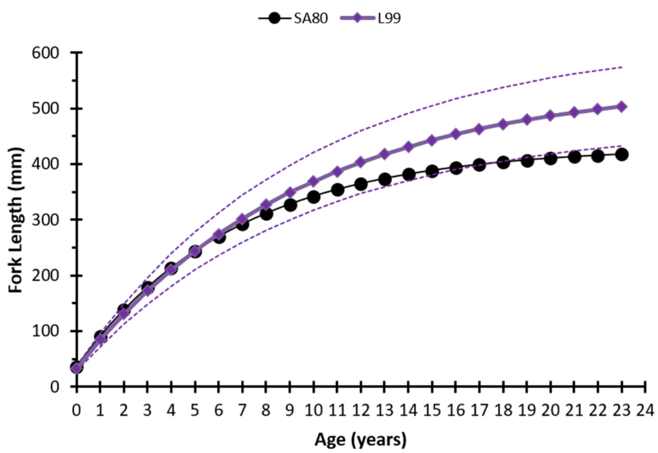


Figure 6.- Simplified flow diagram of the REEFS (Reef Ecosystem Exploited Fishery Simulator) length-based population model. Boxes represent state variables, solid arrows denote material flows (e.g., recruitment, growth, mortality, and biomass), and dashed arrows indicate information flows among model components used to estimate fishery production, stock reproductive capacity, and sustainability benchmarks.

(A) Yellowtail snapper



(B) Queen triggerfish



(C) Stoplight parrotfish

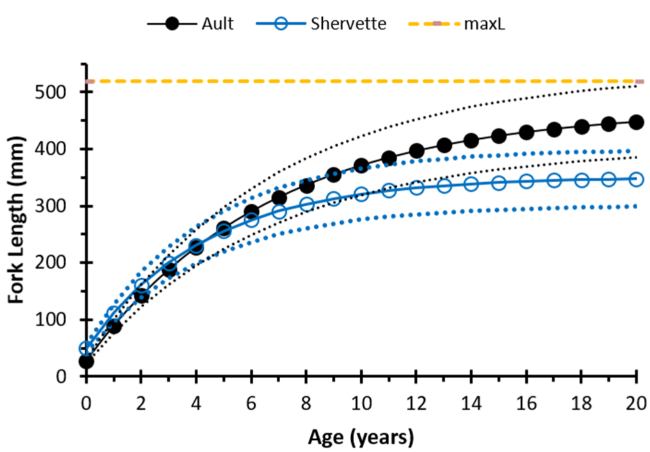


Figure 7.- Fork length-at-age relationships (solid lines) and corresponding ±7% coefficient of variation (CV) size-at-age distributions (dotted lines) used in the stochastic length-based population model for: (A) yellowtail snapper; (B) queen triggerfish; and (C) stoplight parrotfish.

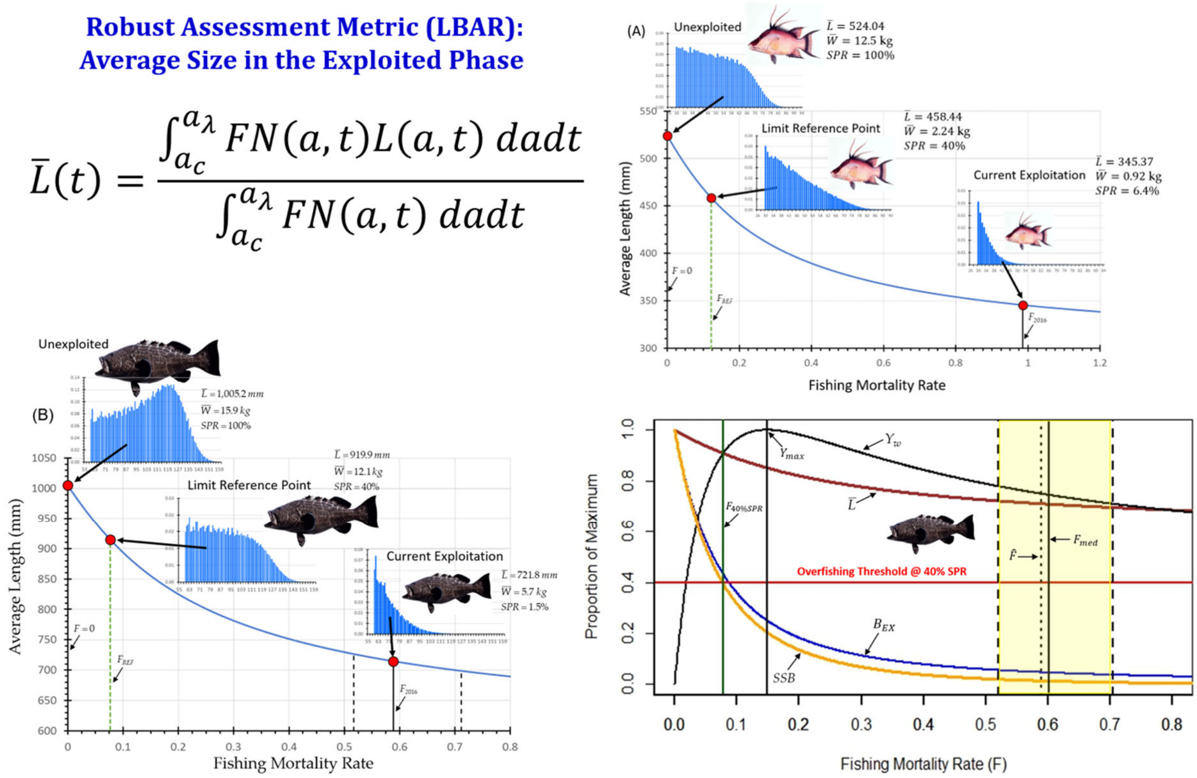


Figure 8.- Conceptual basis of the LBAR (Length-Based Assessment of total mortality) algorithm, illustrating the relationship between average length in the exploited phase $\bar{L}$ and fishing mortality (Ault and Ehrhardt, 1991; Ehrhardt and Ault, 1992). Predicted responses of $\bar{L}$ to increasing fishing mortality are shown for two representative coral reef species: (A) hogfish; and (B) black grouper.

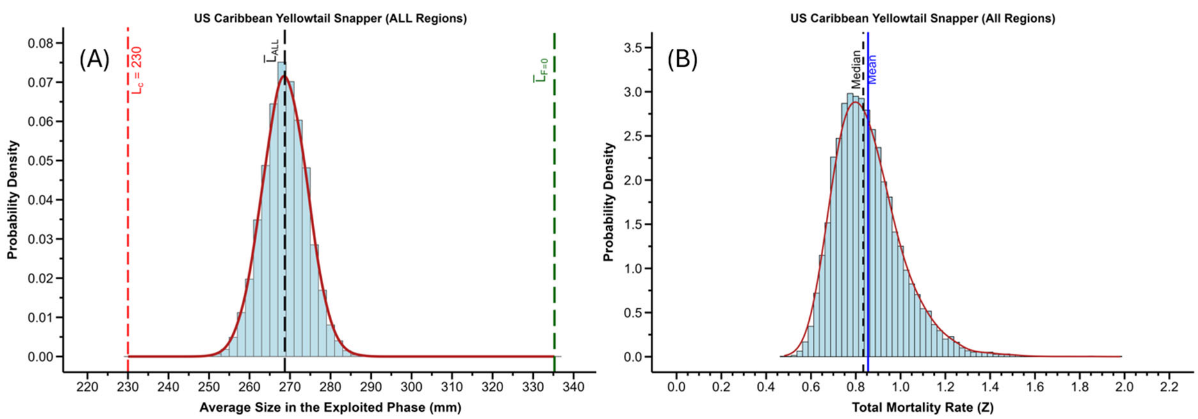


Figure 9.- Probability density distributions for U.S. Caribbean yellowtail snapper showing: (A) average length in the exploited phase $\bar{L}$ for all island regions combined (see Table 1A); and (B) total mortality rate (Z) estimated using the LBAR algorithm.

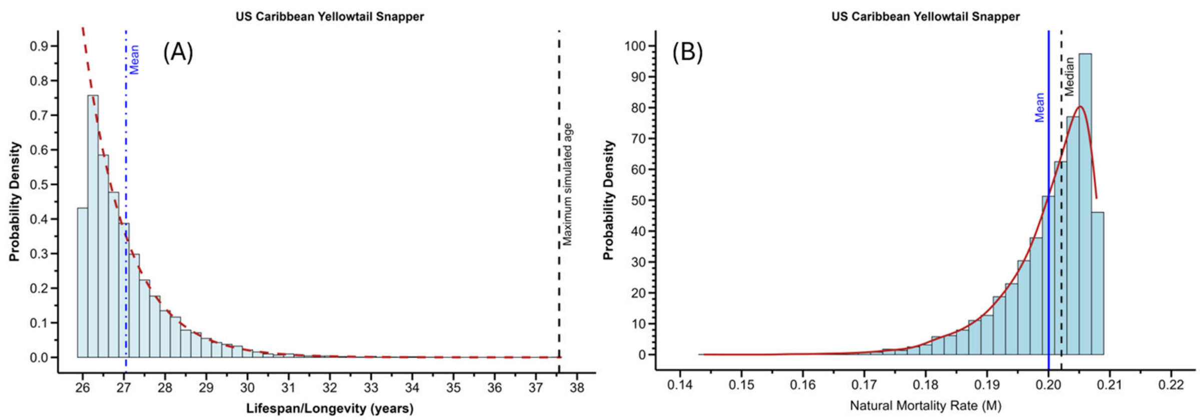


Figure 10.- Conversion of the longevity probability density distribution to the corresponding natural mortality rate (M) probability density distribution: (A) longevity probability density distribution derived using Equations (6)–(8); and (B) resulting probability density distribution of the natural mortality rate ((M)).

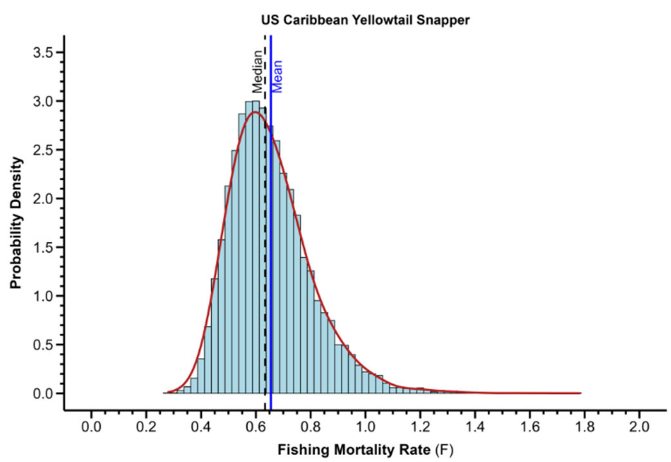


Figure 11.- Resulting Monte Carlo probability density distribution of fishing mortality rates (F), calculated as the difference between total and natural mortality $(F = Z - M)$..

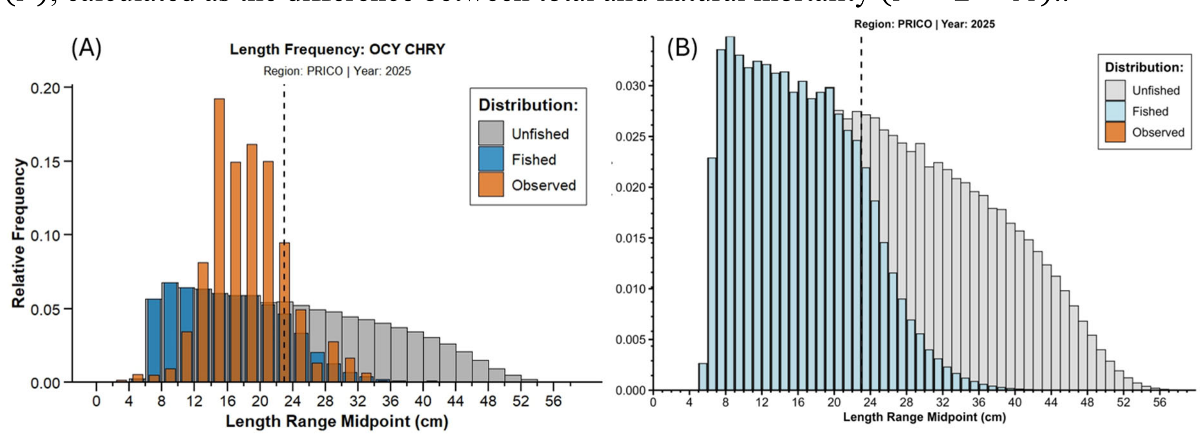


Figure 12.- Size-structured abundance distributions for U.S. Caribbean yellowtail snapper in Puerto Rico showing: (A) observed abundance-at-length distribution (orange) compared with model-predicted exploited and unexploited (F = 0) population distributions; and (B) enlarged view of the model-predicted exploited and unexploited abundance-at-length distributions.

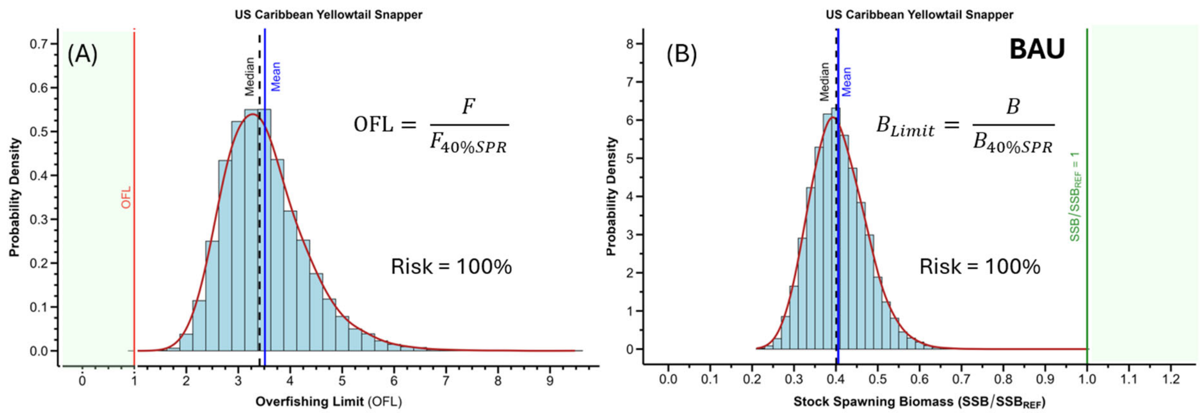


Fig. 13.- Baseline business-as-usual (BAU) conditions for U.S. Caribbean yellowtail snapper (all island regions combined) showing sustainability risk distributions for: (A) the overfishing limit (OFL); and (B) the spawning stock biomass limit (B_{Limit}). The green regions represent sustainable conditions ($\text{i.e.}, \text{OFL} < 1$ and $B_{Limit} > 1$). Under BAU conditions, the estimated sustainability risk is 100% for both management metrics.

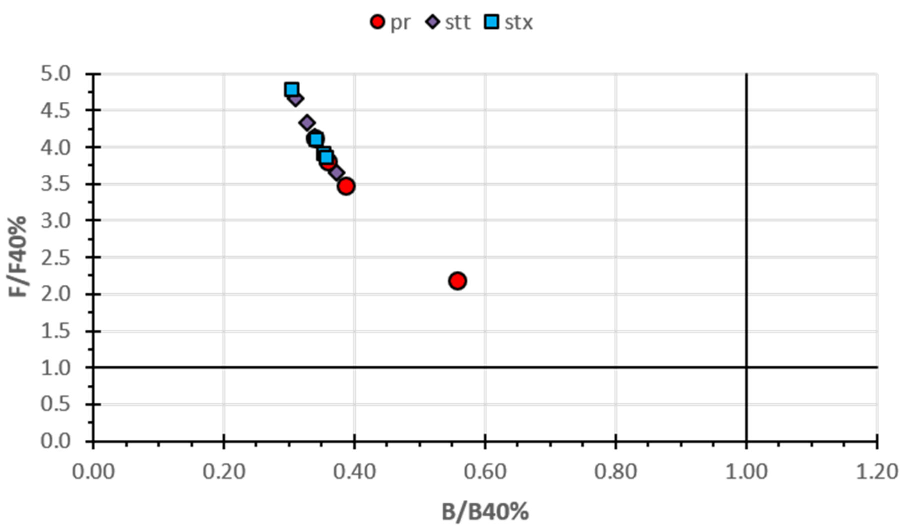


Fig. 14.- Kobe plot for U.S. Caribbean yellowtail snapper under baseline business-as-usual (BAU) management, showing annual stock status for the three island regions: (A) Puerto Rico (PR); (B) St. Thomas–St. John (STT); and (C) St. Croix (STX). Points represent annual Reef Fish Visual Census (RVC) survey estimates for 2016–2025 relative to the fishing mortality and spawning biomass sustainability reference points.

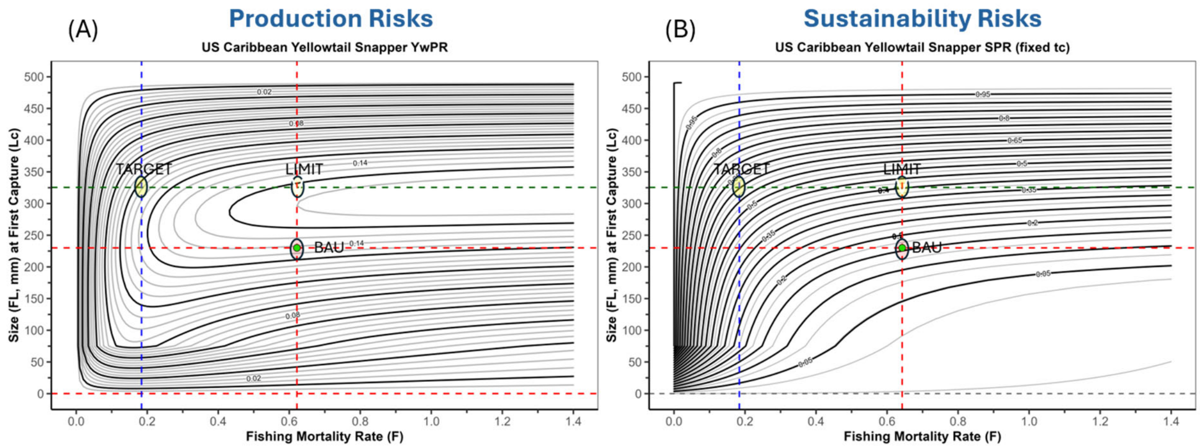


Figure 15.- Management strategy isopleths for U.S. Caribbean yellowtail snapper showing: (A) yield per recruit (Y_w/R); and (B) spawning potential ratio (SPR) as functions of fishing mortality (F) and minimum length at first capture (L_c). The **Limit** strategy increases L_c to achieve a minimum SPR of 40%, whereas the **Target** strategy further reduces fishing mortality to F_{REF} while L_c at or above the Limit strategy, resulting in SPR > 40%. Horizontal dashed lines indicate the L_c for the business-as-usual (BAU; lower red line) and Limit (upper green line) strategies. The vertical dotted line denotes F_{REF}.

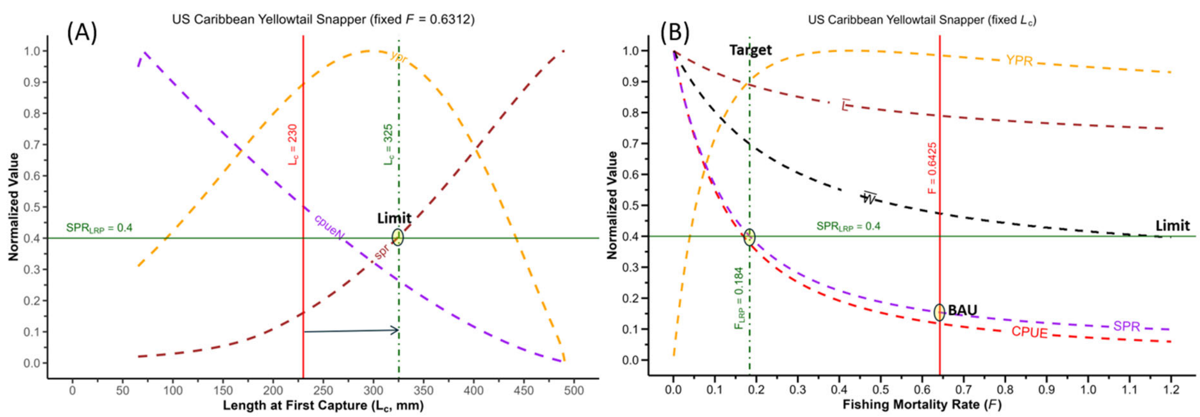


Figure 16.- Relationships among key population performance metrics for U.S. Caribbean yellowtail snapper as functions of fishing mortality (F) at $L_c = 230$ mm fork length (FL): yield in weight (Y_w, dashed yellow line); exploitable biomass (B_{EX}; solid green line); spawning potential ratio (SPR; dashed purple line), and average length in the exploited phase (L, solid brown line). All metrics were normalized to their respective maximum values. The horizontal red line indicates the current business-as-usual (BAU; 2025) exploitation level, and the vertical green line denotes the fishing mortality limit reference point, F_{REF}, corresponding to the 40% SPR sustainability threshold.

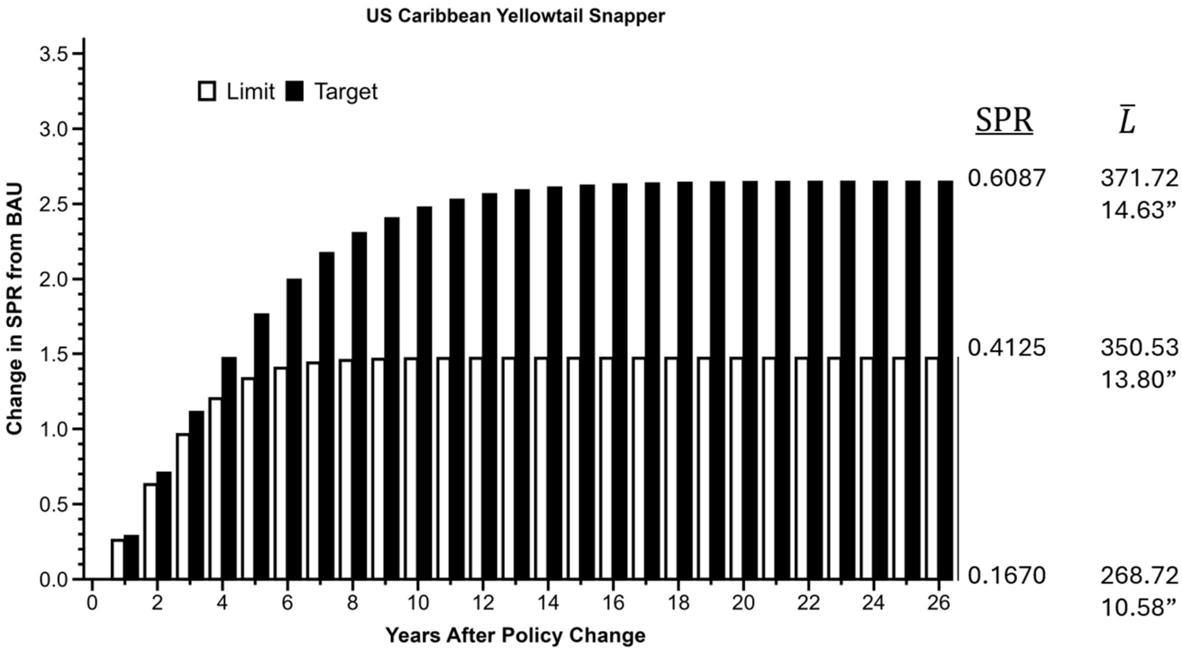


Figure 17.- Simulated recovery trajectories following implementation of the **Limit** and **Target** management strategies at Year 0 for U.S. Caribbean yellowtail snapper: (A) change in yield per recruit (Y_w/R) relative to business-as-usual (BAU) conditions; and (B) change in spawning potential ratio (SPR) relative to BAU. The **Limit** strategy increases minimum length at first capture (L_c) to achieve a minimum SPR of 40%, whereas the **Target** strategy combines the increased L_c with a reduction in fishing mortality to F_{REF}.

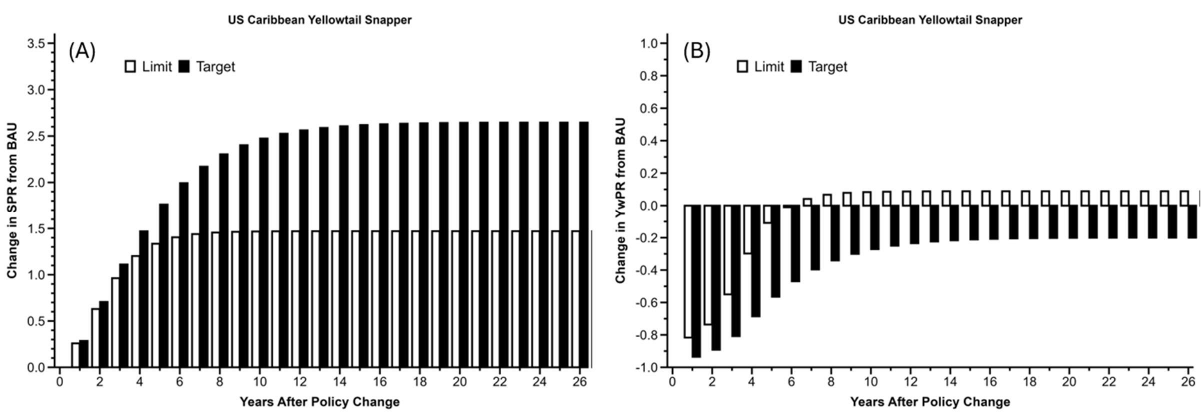


Figure 18.- Simulated recovery trajectories following implementation of the **Limit** and **Target** management strategies at Year 0 for U.S. Caribbean yellowtail snapper: (A) change in spawning potential ratio (SPR); and (B) change in yield per recruit (Y_w/R), both relative to initial business-as-usual (BAU) conditions. The **Limit** strategy increases L_c to achieve a minimum SPR of 40%, whereas the **Target** strategy further reduces fishing mortality to F_{REF} while L_c at or above the Limit strategy, resulting in SPR > 40%.

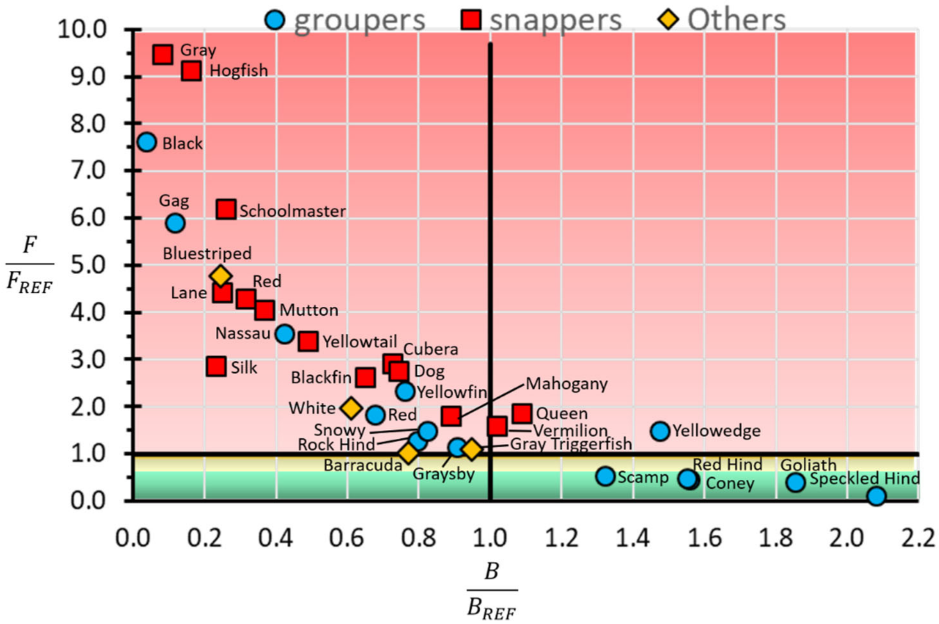


Fig. 19. Kobe strategy plot showing median exploitation status (2012-2016) of 15 key exploited coral reef fishes from southern Florida. The joint limit reference point is defined by $\frac{F}{F_{\mathrm{REF}}} = \frac{B}{B_{\mathrm{REF}}} = 1$. Overfishing occurs in the upper left quadrant III, where $F/F_{\mathrm{REF}} > 1$ and $B/B_{\mathrm{REF}} < 1$. The lower right quadrant (I) represents the target region for sustainable fisheries, characterized by $F/F_{\mathrm{REF}} < 1$, $B/B_{\mathrm{REF}} > 1$, and SPR > 0.4.

Table 1.- Principal exploited coral reef fish species and regional management units included in the U.S. Caribbean length-based risk analysis (LBRA). The three study regions are Puerto Rico (PR), St. Thomas–St. John (STT), and St. Croix (STX).

			REGION		
		Puerto Rico	**St. Thomas/St. John**	**St. Croix**	**All**
Survey Area (km^2)		1,126.21	178.81	248.46	1,553.48
Species	Code				
1. Yellowtail snapper	*Ocy chry*				
2. Queen triggerfish	*Bal vetu*				
3. Stoplight parrotfish	*Spa viri*				

Table 1.- Population demographic parameters, variables, equations, and units used in the estimation–simulation risk analysis of U.S. Caribbean reef fish populations. Equation numbers in brackets correspond to those presented in the text. Equations designated T-1, T-2, etc., identify relationships summarized in this table and referenced throughout the Methods.

Symbol	Definition	Computational Formula	Units	Eq. No.
a	Cohort age class ($a = 0, \cdots, a_\lambda$)		months	
Δa	Model age step		months	
Δt	Model time step		months	
$L(a,t)$	Length at age a and time t	$L(a,t) = L_\infty\left(1 - e^{-K(a-a_0)}\right)$	mm FL	T-1
L_∞	Asymptotic length		mm FL	
K	Brody growth coefficient		per year	
a_0	Age at which length equals zero		years	
$W(a,t)$	Weight at age a and time t	$W(a,t) = \alpha\left(L(a,t)\right)^\beta$	kg	T-2
α	Scalar coefficient of weight-length function		dimensionless	
β	Power coefficient of weight-length function		dimensionless	
a_λ	Maximum age (under exploitation)		years	
L_m	Length at 50% maturity		mm FL	
a_r	Age at recruitment to population (= age 0)		months	
L_r	Length at recruitment to population	$L_r = L_\infty\left(1 - e^{-K(a_r-a_0)}\right)$	mm FL	
$N(a,t)$	Numbers (abundance) at age $a + \Delta a$ at time $t + \Delta t$	$N(a + \Delta a, t + \Delta t) = N(a,t)e^{-\left((M(a,t)+F(a,t)\right)}$	number of fish	T-3
$F(a,t)$	Fishing mortality rate at age a at time t		per year	
$M(a,t)$	Natural mortality rate at age a at time t		per year	
$Z(a,t)$	Total mortality rate at age a at time t	$Z(a,t) = M(a,t) + F(a,t)$	per year	
$\hat{Z}(t)$	Total mortality rate estimated from $\bar{L}$	$\left[\frac{L_\infty - L_\lambda}{L_\infty - L_c}\right]^{\frac{\hat{Z}(t)}{K}} = \frac{\hat{Z}(t)\left(L_c - \bar{L}(t)\right) + K\left(L_\infty - \bar{L}(t)\right)}{\hat{Z}(t)\left(L_\lambda - \bar{L}(t)\right) + K\left(L_\infty - \bar{L}(t)\right)}$	per year	[2]
$\bar{L}(t)$	Average length in the exploited phase at time t			
L_c	Minimum length at first capture		mm FL	
L_λ	Mean length at maximum age	$L_\lambda = L_\infty\left(1 - e^{-K(a_\lambda-a_0)}\right)$	mm FL	T-4
$\bar{\bar{L}}$	Composite $\bar{L}$ from empirical sampling surveys		mm FL	
$S(a)$	Survivorship to age a	$S(a) = \frac{N(a)}{N(a_r)} = e^{-Z(a-a_r)}$	dimensionless	[3]
$\widehat{M}$	Natural mortality rate estimated from $\hat{a}_\lambda$	$\widehat{M} = -\ln(0.05)/\hat{a}_\lambda$	per year	[4]
$\hat{a}_\lambda$	Observed maximum age		years	
$\tilde{a}_\lambda$	Theoretical maximum age			
$\hat{F}$	Fishing mortality rate estimated from $\hat{Z}$ and $\widehat{M}$	$\hat{F} = \hat{Z} - \widehat{M}$	per year	

F_{med}	Median of distribution of *F*		per year	
$N(L)$	Theoretical length-based population model	$N(L) = \int_t^{t+\Delta t}\int_{a_r}^{a_\lambda} R(\tau - a)S(a)\,\theta(a)p(L\|a)\text{dadt}$	numbers	T-5
$R(\tau - a)$	Recruits lagged back to birth		numbers	
$\theta(a)$	Sex ratio at age *a*	$\theta(a) = 1$	dimensionless	
$\bar{L}(a)$	Mean length at midpoint of age interval $a + \Delta a$	$\bar{L}(a) = L_\infty\left(1 - e^{-K\left((a+0.5\Delta a)-a_0\right)}\right)$	mm FL	
$p(L\|a)$	Probability of being length *L* given age *a*	$p(c \le \bar{L}(a) \le d) = \Phi\left(\frac{d - \bar{L}(a)}{\sigma(a)}\right) - \Phi\left(\frac{c - \bar{L}(a)}{\sigma(a)}\right)$	dimensionless	T-6
c	Lower bound of length distribution at age *a*			
d	Upper bound of length distribution at age *a*			
$\Phi(\,)$	Cumulative Normal distribution			
$\bar{W}(a)$	Mean weight at midpoint of age interval $a + \Delta a$	$\bar{W}(a) = \alpha\left(\bar{L}(a)\right)^\beta$	kg	
$\phi(L)$	Selectivity at length *L*	$\phi(L) = 1$	dimensionless	
$\bar{N}(t)$	Average population abundance at time *t*	$\bar{N}(t) = \int_t^{t+\Delta t}\int_{a_r}^{a_\lambda} N(a,t)\left(1 - e^{-Z(a,t)}\right)/Z(a,t)\text{dadt}$	numbers	
$B_{EX}(L_c, t)$	Exploitable population biomass	$B_{EX}(L_c,t) = \int_{L_c}^{L_\lambda} N(L\|a,t)W(L\|a,t)\phi(L)\,dL$	mt	[9]
$\bar{N}(L,t)$	Average abundance (numbers) at length at time *t*	$\bar{N}(L,t) = \sum_{a_r}^{a_\lambda} p(L\|a,t)\,\bar{N}(a,t)$	numbers	T-7
$\bar{B}(t)$	Average population biomass at time *t*	$\bar{B}(t) = \int_t^{t+\Delta t}\int_{a_r}^{a_\lambda} \bar{N}(a,t)\,\bar{W}(a,t)\text{dadt}$	mt	
$Y_w(F, L_c, t)$	Yield in weight at time *t*	$Y_w(F,L_c,t) = F(t)B_{EX}(L_c,t)$	mt	[10]
SSB	Spawning (mature) stock biomass	$SSB(t) = \int_{L_m}^{L_\lambda} B(L\|a,t)\,dL$	mt	[11]
SPR	Spawning potential ratio	$SPR = SSB_{\hat{F}}/SSB_{F=0}$	dimensionless	[12]
F_{REF}	Fishing mortality rate at reference SPR		per year	
$\hat{\bar{L}}$	Model projected $\bar{L}$	$\hat{\bar{L}} = \frac{\int_{L_c}^{L_\lambda}\bar{N}(L,t)LdL}{\int_{l_c}^{L_\lambda}\bar{N}(L,t)dL}$	mm FL	T-8
F/F_{REF}	Current to reference *F* (Overfishing limit, OFL)		dimensionless	
B/B_{REF}	Current to reference spawning biomass		dimensionless	[13]

Table 2.- Life-history demographic parameters for three exploited coral reef fish species from the U.S. Caribbean used in the length-based sustainability risk assessment (LBRA): (A) yellowtail snapper; (B) queen triggerfish; and (C) stoplight parrotfish. Parameter definitions, equations, and units are provided in Table 1.

(A) Yellowtail snapper (yt)

Symbol	Definition	Value	Units
L_∞	Asymptotic length (Primary)	502.5	mm FL
K	Brody growth coefficient (Primary)	0.139	per year
a_0	Age at which length equals zero (Primary)	-0.960	years
L_∞	Asymptotic length	508.0	mm FL
K	Brody growth coefficient	0.120	per year
a_0	Age at which length equals zero	-2.730	years
W_∞	Asymptotic weight	2.181	kg
α	Scalar coefficient of weight-length function	4.000E-05	dimensionless
β	Power coefficient of weight-length function	2.8642	dimensionless
a_λ	Maximum observed age (under exploitation)	26	years
S_λ	Average survivorship probability to a_λ	0.0045	dimensionless
L_r	Length at first recruitment to population	25.0	mm FL
L_m	Length at 50% maturity	194.0	mm FL
$\bar{L}$	Average length in the exploited phase	268.7272	mm FL
L_c	Minimum length at first capture	230.0	mm FL
L_λ	Mean length at maximum age	490.65	mm FL
W_λ	Mean weight at maximum age	2.0369	kg
$\bar{R}$	Population recruitment	276,609	fish per year
$\widehat{M}$	Natural mortality rate estimated from $\hat{a}_\lambda$	0.2078338	per year

(B) Queen triggerfish (qt)

Symbol	Definition	Value	Units
K	Brody growth coefficient (SA80)	0.150	per year
L_∞	Asymptotic length (L99)	550.0	mm FL
K	Brody growth coefficient (L99)	0.105	per year
a_0	Age at which length equals zero	-0.585	years
W_∞	Asymptotic weight	1.4662	kg
α	Scalar coefficient of weight-length function	5.517808E-08	dimensionless
β	Power coefficient of weight-length function	2.8690	dimensionless
a_λ	Maximum observed age (under exploitation)	23	years
S_λ	Average survivorship probability to a_λ	0.015	dimensionless
L_r	Length at first recruitment to population	25.0	mm FL
L_m	Length at 50% maturity	214.0	mm FL
$\bar{L}$	Average length in the exploited phase	290.46829	mm FL
L_c	Minimum length at first capture	200.0	mm FL
L_λ	Mean length at maximum age	417.50	mm FL
W_λ	Mean weight at maximum age	1.3633	kg
$\bar{R}$	Population recruitment	793.e+03	fish per year
$\widehat{M}$	Natural mortality rate estimated from $\hat{a}_\lambda$	0.1825959	per year

(C)

Stoplight parrotfish (slp)

	SEDAR 84-STX	Ault - STX	Units
Parameter	Case 1 - SLP	Case 2 - SLP	
L_∞	332.0	470.0	mm
K	0.39	0.15	yr^{-1}
a_0	-0.06	-0.40	years
W_∞	0.6512	2.2080	kg
α	3.18e-05	3.70e-05	kg
β	2.90	2.91	kg
a_λ	20	20	years
S_λ	0.05	0.05	yr^{-1}
M	0.14979	0.14979	yr^{-1}
L_r	7.68	27.37	mm
L_m	153	153	mm
maturity ogive			knife-edged
$\bar{L}$	285.69	285.60	mm
L_c	230	230	mm
Selectivity ogive			knife-edged
L_λ	331.87	447.96	mm
W_λ	0.6505		kg
$\bar{R}$	66,000	66,000	number
Z	0.3227	0.4965	yr^{-1}
B0	141,363.98	86,698.13	kg
F	0.1729	0.3467	yr^{-1}
F40%SPR	0.22505	0.17677	yr^{-1}
SPR $(\tilde{\mathrm{L}})$	0.4681 (284.73)	0.2408 (283.39)	dimensionless

Table 3.- Length-based risk analysis (LBRA) estimates of total (Z), natural (M), and fishing (F) mortality rates by survey year for three exploited coral reef fish species in the U.S. Caribbean, derived from Reef Fish Visual Census (RVC) sampling. Estimates are presented for the three island regions: Puerto Rico (PR), St. Thomas–St. John (STT), and St. Croix (STX).

(A) Yellowtail snapper (yt)

Yellowtail Snapper			8/2/2026 20:55							REGION (weighted by sample-size)			OVERALL (weighted by area)			
region	year	lbar	se	n	cv	Z	F	SPR	area	lbar	se	cv	lbar	se	n	cv
	2019	26.84493389	0.41994403	203	0.0156	0.8461	0.6383	0.1607		26.9852	0.5579	0.0207				
pr	2021	28.04906915	0.51051300	234	0.0182	0.6112	0.4034	0.2290	1126.21							
	2023	26.61553303	0.85995010	248	0.0323	0.9086	0.7008	0.1499								
	2025	26.43016852	0.40338298	232	0.0153	0.9652	0.7574	0.1417					LBAR(F = 0)	335.2742		
avg		**26.98492615**	**0.54844752**	**229**	**0.0204**	**0.8328**	**0.6250**	**0.1703**								
	2019	26.71988225	0.39018113	322	0.0146	0.8792	0.8567	0.1299		26.8178	0.5272	0.0197	26.872715	0.542152	258	0.0202
stt-stj	2021	26.31211126	0.41501966	165	0.0158	1.0046	0.6714	0.1548	178.81							
	2023	26.42247190	0.59659463	287	0.0226	0.9677	0.7968	0.1366					Z =	0.8391		
	2025	27.48964074	0.65291667	340	0.0238	0.7047	0.7599	0.1414					M =	0.2078		
avg		**26.73602654**	**0.51367802**	**279**	**0.0192**	**0.8891**	**0.7712**	**0.1407**								
													F =	0.6312		
	2019	26.55320288	0.64041504	314	0.0241	0.9270	0.7192	0.1471		26.4022	0.4817	0.0182				
stx	2021	26.58449455	0.06653371	148	0.0025	0.9177	0.7099	0.1485	248.46				B =	85,775		
	2023	26.08627226	0.60610469	275	0.0232	1.0883	0.8805	0.1274					**SPR =**	**0.1621**		
	2025	26.44073091	0.41206290	325	0.0156	0.9619	0.7540	0.1422								
avg		**26.41617515**	**0.43127909**	**266**	**0.0164**	**0.9737**	**0.7659**	**0.1413**								

(B) Queen triggerfish (qt)

Queen Triggerfish			8/3/2026 16:19							REGION (weighted by sample-size)			OVERALL (weighted by area)			
region	year	lbar	se	n	cv	Z	F	SPR	area	lbar	se	cv	lbar	se	n	cv
	2019	31.07309211	1.11908788	203	0.0360	0.3076	0.0726	0.3568		30.2811	0.6514	0.0215				
pr	2021	31.35424995	0.67782833	234	0.0216	0.2928	0.0579	0.3880	1126.21							
	2023	30.33359689	0.55773406	248	0.0184	0.3511	0.1162	0.2836		**Z**	**F**	**SPR**				
	2025	28.44972460	0.31561018	232	0.0111	0.5113	0.2764	0.1469		0.3545	0.1196	0.2742				
avg		**30.30266589**	**0.66756511**	**229**	**0.0218**	**0.3657**	**0.1308**	**0.2938**								
	2019	30.99045529	0.67287143	322	0.0217	0.3121	0.0771	0.3480		31.3186	0.5751	0.0184	30.553308	0.646775	258	0.0212
stt-stj	2021	30.39228565	0.77748450	165	0.0256	0.3474	0.1124	0.2891	178.81							
	2023	31.70719546	0.52764291	287	0.0166	0.2754	0.0405	0.4304		**Z**	**F**	**SPR**	Z =	0.3374		
	2025	31.75101781	0.42444808	340	0.0134	0.2734	0.0384	0.4360		0.2946	0.0597	0.3842	M =	0.2349		
avg		**31.21023855**	**0.60061173**	**279**	**0.0193**	**0.3021**	**0.0671**	**0.3759**								
													F =	0.1025		
	2019	31.20789386	0.61622377	314	0.0197	0.3004	0.0655	0.3714		31.2362	0.6774	0.0217				
stx	2021	30.09024616	0.98547684	148	0.0328	0.3673	0.1323	0.2623	248.46				**SPR =**	**0.3039**		
	2023	29.89252551	0.40674087	275	0.0136	0.3811	0.1462	0.2458		**Z**	**F**	**SPR**				
	2025	32.92241838	0.82525921	325	0.0251	0.2234	-0.0115	0.5138		0.2989	0.0640	0.3746				
avg		**31.02827098**	**0.70842517**	**266**	**0.0228**	**0.3181**	**0.0831**	**0.3483**								
M (0.0045) =	0.234943						**SPR avg**	**0.3393**								

(C) Stoplight parrotfish (slp)

Stoplight Parrotfish			8/3/2026 14:15							REGION (weighted by sample-size)			OVERALL (weighted by area)			
region	year	lbar	se	n	cv	Z	F	SPR	area	lbar	se	cv	lbar	se	n	cv
	2019	28.68708603	0.42754863	203	0.0149	0.4822	0.2120	0.3518		28.3586	0.5154	0.0182				
pr	2021	28.23539134	0.42823695	234	0.0152	0.5372	0.2670	0.2957	1126.21							
	2023	27.24159858	0.58580343	248	0.0215	0.6987	0.4285	0.2038		**Z**	**F**	**SPR**				
	2025	29.38937782	0.60479679	232	0.0206	0.4114	0.1412	0.4626		0.5213	0.2511	0.3100				
avg		**28.38836344**	**0.51159645**	**229**	**0.0180**	**0.5324**	**0.2622**	**0.3285**								
	2019	28.27203949	1.26189673	322	0.0446	0.5324	0.2622	0.3000		28.2853	0.7778	0.0275	28.442504	0.583131	258	0.0205
stt-stj	2021	27.24899213	0.32648217	165	0.0120	0.6972	0.4270	0.2043	178.81							
	2023	28.27475796	0.55141279	287	0.0195	0.5320	0.2619	0.3001		**Z**	**F**	**SPR**	Z =	0.5109		
	2025	28.80952350	0.72958202	340	0.0253	0.4687	0.1985	0.3680		0.5307	0.2605	0.3014	M =	0.2702		
avg		**28.15132827**	**0.71734343**	**279**	**0.0254**	**0.5576**	**0.2874**	**0.2931**								
													F =	0.2407		
	2019	29.39462140	0.66750073	314	0.0227	0.4110	0.1408	0.4634		28.9361	0.7502	0.0259				
stx	2021	29.45132995	0.92647046	148	0.0315	0.4059	0.1357	0.4738	248.46				**SPR =**	**0.3201**		
	2023	27.85819873	0.57832964	275	0.0208	0.5908	0.3206	0.2562		**Z**	**F**	**SPR**				
	2025	29.17056269	0.89513262	325	0.0307	0.4318	0.1617	0.4245		0.4553	0.1851	0.3875				
avg		**28.96867819**	**0.76685836**	**266**	**0.0264**	**0.4599**	**0.1897**	**0.4045**								
M (0.0045) =	0.2702						**SPR avg**	**0.3420**								

Table 4.- Length-based risk analysis (LBRA) sustainability metrics for three exploited coral reef fish stocks in the U.S. Caribbean. Parameter symbols are defined in Table 1. Sustainability criteria are $\frac{F}{F_{\text{REF}}} < 1$, $\frac{B}{B_{\text{REF}}} > 1$, and SPR > 0.4.

Species	$\hat{F}$	F_{med}	F_{REF}	$\hat{\bar{L}}_{\hat{F}}$	$\hat{\bar{L}}_{F=0}$	$\hat{\bar{L}}_{F_{\text{REF}}}$	$\hat{F}/F_{\text{REF}}$	$B_{\hat{F}}/B_{\text{REF}}$	SPR
Yellowtail snapper (all)	0.6312	0.6405	0.1878	268.73	337.18	300.10	3.513	0.4006	0.1621
Puerto Rico	0.6250								0.1703
St. Thomas/St. John	0.7712								0.1407
St. Croix	0.7639								0.1413
Queen triggerfish (all)	0.1025		0.0527	305.53	320.69	291.31			0.3039
Puerto Rico	0.1196								0.2742
St. Thomas/St. John	0.0597								0.3842
St. Croix	0.0690								0.3748
Stoplight parrotfish (all)	0.2407		0.1768	284.43	337.58	302.73			0.3201
Puerto Rico	0.2511								0.3100
St. Thomas/St. John	0.2605								0.3014
St. Croix	0.1851								0.3875